Simultaneous Estimation of WCE Moving Distance and Heading Direction Based on RSSI-based Localization

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ABSTRACT

In this paper, we propose a simultaneous moving distance and heading direction estimation method for wireless capsule endoscope (WCE) system only with RSSI measurement data, which can be obtained as a fundamental function of wireless communications. This paper first focuses on an RSSI-based WCE location tracking method with a particle filter algorithm. Then, in order to accurately estimate the moving distance and heading direction, the proposed method detects the waypoints (pass points) based on the time-series estimated WCE location information, on which the WCE moving in gastrointestinal tract. Consequently, both estimation can be realized with connecting the estimated waypoints. From our computer simulation results, the proposed method can achieve good estimation performances of the moving distance and heading direction with the accuracies of several centimeters and several degrees, respectively, without specific additional sensor devices.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*

General Terms

Measurement

Keywords

Body area network, wireless capsule endoscope, localization.

1. INTRODUCTION

Recently, body area network (BAN) technology has been widely studied and applied to medical or healthcare applications [1]. In particular, a wireless capsule endoscope (WCE) system is an important application in implant BAN technologies [2–6]. A WCE contains a color camera, a battery, lights, and a transmitter. It moves depending on peristalsis and provides videos or photographs taken in a gastrointestinal (GI) tract.

Considering a realistic situation for WCE systems, the WCE location information is convenient to doctors for diagnosis. In addition to the location information, it is important to estimate the moving distance and the heading direction as well. If we can obtain not only the location information but also the moving distance, the correctness of diagnosis in a small intestine would be improved because tumor location should be more clearly identified. Additionally, the heading direction information allows us to realize highly effective wireless power transmission, which can be expected to solve the energy consumption problem in WCE systems.

There are some ways to obtain the moving distance and heading direction of a WCE. For example, it is a simple way to equip sensor devices into the WCE, such as triaxial accelerometer sensor for moving distance measurement and gyro sensor for heading direction detection. However, it is unrealistic to add such sensor devices to the WCE due to its small size. For avoiding to introduce additional devices on the WCE, this paper aims to estimate them only with received signal strength indicator (RSSI) data, which can be measured as a fundamental function of wireless communications. As for WCE location estimation methods, some radio frequency (RF)-based localization methods have been proposed in literature [3, 4]. Also, we have so far developed an RSSI-based WCE tracking method with a particle filter algorithm, and demonstrated its localization accuracy of 7 mm [5]. In this paper, we propose a moving distance and heading direction estimation method based on the time-series location estimated by the RSSI-based localization, and evaluate its performance through computer simulations.

The rest of this paper is organized as follows: In Section 2, we introduce an RSSI-based WCE localization method with a particle filter. Section 3 proposes an estimation method of the moving distance and heading direction. The performance evaluation is performed in Section 4, and we finally conclude this paper in Section 5.

2. RSSI-BASED LOCALIZATION METHOD FOR WCE WITH PARTICLE FILTER

2.1 System model

We assume that M receivers are located on patient's body and a WCE is located inside of small intestine. The location of the m-th receiver is represented as $\boldsymbol{r}_m$ and the WCE location is represented as $\boldsymbol{r}$. We assume 400MHz medical implant communication services (MICS) band signals as transmit signals. The location information of all receivers are

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known in advance, on the other hand, the WCE location is unknown. Their three-dimensional locations are defined as

$$\boldsymbol{r} = [x, y, z]^T \quad (1)$$

$$\boldsymbol{r}_m = [x_m, y_m, z_m]^T \quad (2)$$

where $(\cdot)^T$ indicates the transpose of $(\cdot)$. We also define RSSI vector as $\boldsymbol{P} = [P_1, \cdots, P_M]$. Here, $\boldsymbol{P}$ obtained on each receiver will be handed over to a localization system.

2.2 RSSI-based location tracking with particle filter

The propagation characteristic of implant BAN signals in MICS band can be well expressed with the following two-layered model [6].

$$\mu(d) = \log \overline{P_r} = \log[\alpha d^{-n}] \quad (3)$$

$$p(P_r|d) = \frac{1}{\sqrt{2\pi}\sigma P_r} \exp\left[-\frac{\{\log P_r - \mu(d)\}^2}{2\sigma^2}\right] \quad (4)$$

where P_r, d are the received power (namely, RSSI) and the distance between the transceivers, respectively. The literature [6] reported the parameters, $\alpha = 10^{-7.5}$, $n = 6.65$ and $\sigma = 5.50$.

Then, we apply the propagation characteristics shown in Eqs. (3) and (4) into a particle filter-based location tracking algorithm. The particle filter algorithm repeats the following four steps within every time interval Δt. In the prediction step of the particle filter, each particle is linearly moved to respective destination depending on random waypoint (pass point) model [5,7] resembling intestinal peristalsis. When a particle reaches its destined waypoint, new destination will be set to it. Besides, the particle is expected to linger in intestine bends for a random amount of time, therefore it stops working for the seconds decided by the uniform distribution $\mathcal{U}(0, 20)$. The update step in the particle filter then executes that importance weight of each particle is updated based on the likelihood function derived in Eq. (4). In order to avoid significant degeneracy, resampling is performed in the particle filter algorithm. Resampling is a process that the negligible particles with low weight are eliminated and effective particles with high weight are duplicated. Finally in the estimation step, the estimated location is calculated with the weighted average of all particles.

3. ESTIMATION METHOD OF MOVING DISTANCE AND HEADING DIRECTION

3.1 Simple moving distance estimation

To simply estimate the moving distance, it can be estimated by integrate the instantaneous velocities of the WCE. In this method, the estimated moving distance $l[n]$ is expressed by

$$l[n] = \sum_{i=1}^{n} \left|\hat{\boldsymbol{r}}[i] - \hat{\boldsymbol{r}}[i-1]\right| \quad (5)$$

where $\hat{\boldsymbol{r}}[i]$ is the estimated location vector calculated by the RSSI-based localization at the time index i. However, because of the WCE forward and back movement, this simple method might not be able to perform accurate direction estimation. For this reason, we propose another method which

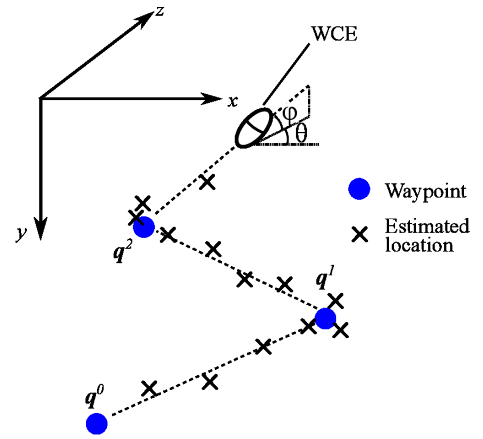

Figure 1: Example of WCE movement.

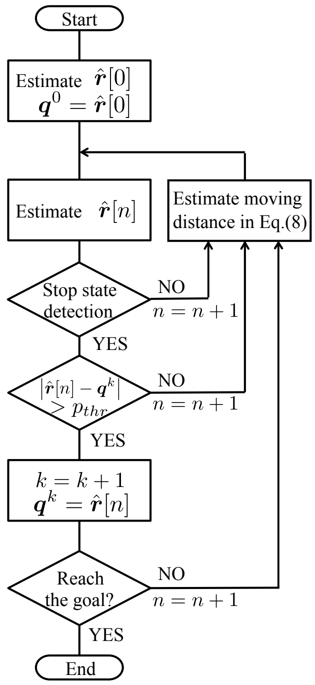

Figure 2: Flowchart of moving distance estimation.

detects the waypoints based on the time-series estimated WCE location information, on which the WCE moving in GI tract and then calculates the moving distance with connecting them.

3.2 Proposed moving distance estimation

Let us define the k-th three-dimensional location of the waypoints as $\boldsymbol{q}^k = [q_x^k, q_y^k, q_z^k]^T$. $\boldsymbol{q}^k$ should be decided as the location where the heading direction of the WCE changes. An example of WCE movement is shown in Fig. 1. In this figure, the WCE moves according to the Random Waypoint model, so it can be seen that we are able to detect the waypoints based on the time-series estimated location information. Also, the flowchart of our proposed method is shown in Fig.2. Our proposed algorithm consists of the following 5 procedures.

Initialization: At the beginning, the first estimated location

Table 1: Simulation parameters.

Number of particles	5000
Resampling threshold	0.7
Transmission interval Δt	0.1 s
Average speed of WCE moving	0.05 cm/s
Variance of the speed	0.005 (cm/s)^2
S	20

$\hat{\boldsymbol{r}}[0]$ is calculated by the particle filter and assigned to the first waypoint $\boldsymbol{q}^0$.

Location estimation: $\hat{\boldsymbol{r}}[n]$ is estimated by the RSSI-based location tracking with the particle filter.

Stop state detection: In this step, we detect whether the WCE moves or stops. This detection is performed as follows:

$$\begin{aligned} &\textit{Detect stop state if } |\boldsymbol{r}'_1[n] - \boldsymbol{r}'_2[n]| < r_{thr} \\ &\textit{Detect moving state otherwise.} \end{aligned}$$

where

$$\boldsymbol{r}'_1[n] = \frac{1}{S/2}\sum_{i=1}^{S/2}\boldsymbol{r}[n-S+i] \quad (6)$$

$$\boldsymbol{r}'_2[n] = \frac{1}{S/2}\sum_{i=S/2+1}^{S}\boldsymbol{r}[n-S+i] \quad (7)$$

In the above equations, S and r_{thr} are the time interval and a threshold of the detection, respectively. Here, the location with the stop state indicates the waypoint.

Waypoint update: The distance between $\hat{\boldsymbol{r}}[n]$ and $\boldsymbol{q}^k$ is calculated. If the distance is larger than p_{thr}, we update the waypoint q^k.In this case, k becomes $k+1$ and $\hat{\boldsymbol{r}}[n]$ is assigned to $\boldsymbol{q}^{k+1}$. Note that the threshold p_{thr} gives the minimum distance between each waypoint.

Moving distance estimation: Finally, using the estimated waypoint $\boldsymbol{q}^k$, the moving distance can be estimated as

$$l[n] = \left|\hat{\boldsymbol{r}}[n] - \boldsymbol{q}^k\right| + \sum_{k'=1}^{k}\left|\boldsymbol{q}^{k'} - \boldsymbol{q}^{k'-1}\right|. \quad (8)$$

3.3 Heading direction estimation

Moreover, we can simultaneously obtain heading direction information of the WCE according to the following equations:

$$\theta^k = \arctan\left(\frac{q_z^{k+1} - q_z^k}{q_x^{k+1} - q_x^k}\right) \quad (9)$$

$$\phi^k = \arctan\left(\frac{q_y^{k+1} - q_y^k}{\sqrt{(q_x^{k+1} - q_x^k)^2 + (q_z^{k+1} - q_z^k)^2}}\right) \quad (10)$$

where θ^k and ϕ^k are the k-th angle in the horizontal plane and the k-th angle of elevation/depression, respectively, as shown in Fig. 1.

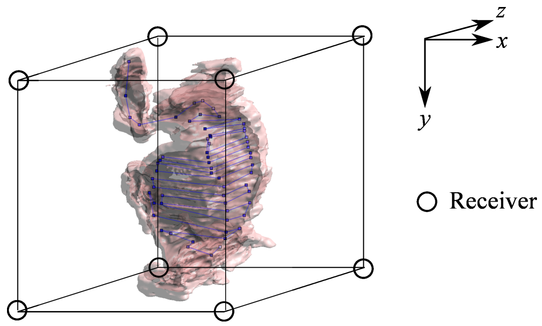

Figure 3: Locus of WCE.

4. PERFORMANCE EVALUATION

4.1 Simulation settings

In order to evaluate the performance of the proposed estimation method, we performed computer simulations. We assumed that a WCE was inside of small intestine and moves in accordance with the random way point model as shown in Fig.3. The location estimation area was a cuboid area whose sizes were 40 cm × 40 cm × 20 cm. Receivers were located on the corners of the cuboid location estimation area. The other simulation parameters are summarized in Table 1.

4.2 Performance evaluation

Fig. 4 illustrates the root mean square (RMS) location estimation error of the RSSI-based tracking with the particle filter in time domain for 10 minutes. Fig. 4 shows that particle filter-based localization can achieve the accuracy of 8.5 mm at 600 s. In contrast, the simple 40-taps FIR (finite impulse response) filter-based localization is also evaluated. The localization accuracy of FIR filter-based localization is about 15 mm, which is twice as large as that of the particle filter-based localization.

Fig. 5 shows the simulation results of the estimated moving distance against the threshold p_{thr} at 10 minutes. From the results, when p_{thr} is 0.02 or 0.03 m, the moving distance can be accurately estimated with any values of r_{thr}. For instance, the estimation error is -0.01479 m when $p_{thr} =$ 0.03[m] and $r_{thr} = 0.003$[m]. Fig. 6 shows the estimated moving distance in time domain. Fig. 6 also includes the result by the simple estimation method shown in Eq.(5). As can be seen from Fig. 6, the performance of the proposed estimation method is much better than that of the simple method. This means that is difficult to estimate the moving distance by simple integration of the instantaneous velocities due to the forward and back movement of the WCE. On the other hand, the proposed method can properly estimate the moving distance by accurately detecting the waypoints.

Finally, let us discuss the performance of the heading direction estimation. Fig. 7 illustrates the RMS heading direction estimation error with $r_{thr} = 0.003$[m] at 10 minutes. When we use the parameter p_{thr} from 0.02 to 0.05 m, RMS heading direction estimation error converges less than 0.5 rad, therefore, the proposed method can estimated the heading direction with the accuracy of less than 10 degrees without equipping special sensor devices into the WCE.

5. CONCLUSIONS

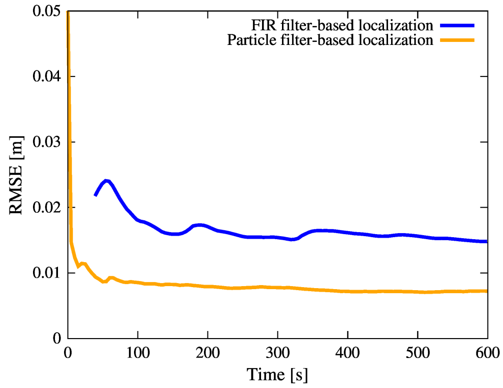

Figure 4: Location estimation accuracy.

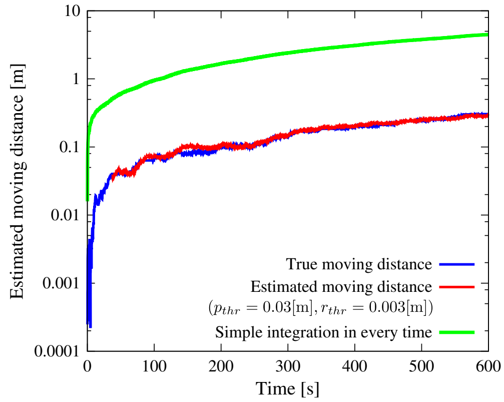

Figure 6: Estimated moving distance in time domain.

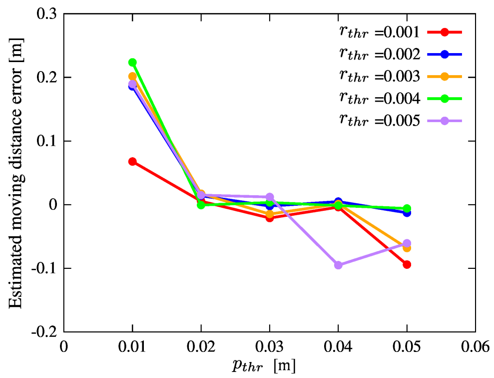

Figure 5: Moving distance estimation performance.

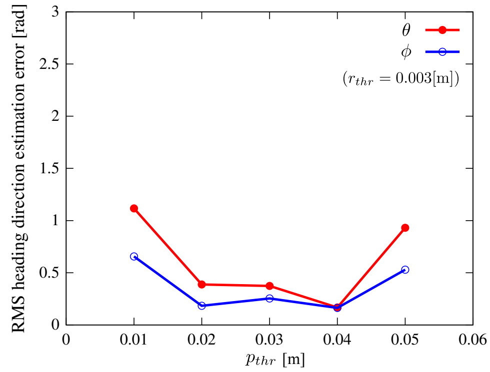

Figure 7: RMS heading direction estimation error.

This paper has proposed a method which simultaneously estimates moving distance and heading direction of a WCE from time-series estimated location information. Then we have evaluated the performances of our proposed method. From the simulation results, the moving distance and the heading direction have been estimated with high accuracies of less than 3 cm and 10 degrees, respectively, without specific sensor devices on the WCE.

6. ACKNOWLEDGMENTS

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